LONG-TERM SETTLEMENT OF TRAFFIC-OPENED EXPRESSWAY ON SOFT GROUND

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ABSTRACT

120 km of expressway in South Korea is constructed on soft ground. This constitutes about 7% of the total length of domestic expressways. Many engineering problems have occurred due to shear failures and settlements in superstructure constructions on soft ground. While technologies for ground improvement have been developed and have evolved into various forms, inevitable long-term settlements have occurred especially in highly embanked expressways and particularly after the opening of traffic. These unpredicted excessive settlements may cause uneven pavement surfaces, an inconvenience and a sense of insecurity while driving, and demand a huge repair cost. Furthermore, the amount of long-term settlement is unknown once the traffic has been opened, rendering it more difficult to manage and repair the expressway. In this study, the actual conditions of a traffic-opened expressway, such as the settlement of the pavement surface and deformations of the embankment, will be investigated. A longitudinal survey, pavement coring, non-destructive testing and site explorations including geophysical methods are applied and methods are suggested to evaluate the long-term settlement of expressways constructed on soft ground.

1. INTRODUCTION

Roads constructed on soft ground are open to traffic when consolidation is completed and the settlement is converged, depending on the accelerated consolidation method used, such as the preloading method, the vertical drain method, and so on. In this case, however, additional settlement is inevitable after traffic has been opened if the elapsed time is not long enough, which is called long-term settlement. This long-term settlement occurs mainly due to the creep deformation of soft soils or still proceeding of “primary” consolidation of soft soils. Besides these original soft ground effects, there are a number of other causes that create settlement under the road being used such as compression of embankment, loss of soil, and poor compaction of the backfill area. Furthermore, a road on soft ground has a superimposed effect on both the original ground effect and other causes.

Figure 1 shows the current condition of settlement occurring in an expressway in Korea during usage. Similar examples are reported in Southeast Asia where the ground is soft in many places. [1] The settlement that occurs during road usage threatens the safety of the road as it induces deformation and cracks on structures and the body itself. Moreover it creates a rugged surface that deteriorates riding comfort and drivability. For this reason, evaluating the settlement of road on soft ground after traffic is open is very important for the management of the road. However, it is difficult to directly measure the settlement of a crowded expressway with high speeding cars, while it is possible during construction by using settlement plate or similar other monitoring sensors. The Korea Expressway Corporation made a very challenging attempt to evaluate the settlement after traffic was opened for the expressway constructed on soft ground.

Figure 1. Bumpy Expressway surface due to settlement during usage

2. SOFT GROUND SECTION OF KOREA EXPRESSWAY

5% of the total expressway under the management of the Korea Expressway Corporation is constructed on soft ground according to geotechnical engineering (Figure 2 and Table 1). Some parts of the Seohaean route (Expressway No. 15), Namhae (Expressway No.10), and the Namhae branch route (Expressway No.104), the Second Gyeongin route (Expressway No.110), the Chungang and Chungang branch routes (Expressway No.551), the Donghae route (Expressway No.65), the Chungbu inland route (Expressway No.45), the Pyungtack-Chungju route (Expressway No.40), the Incheon International Airport route (Expressway No.130), and the Nonsan-Chunan route (Expressway No.25) are located on soft ground.

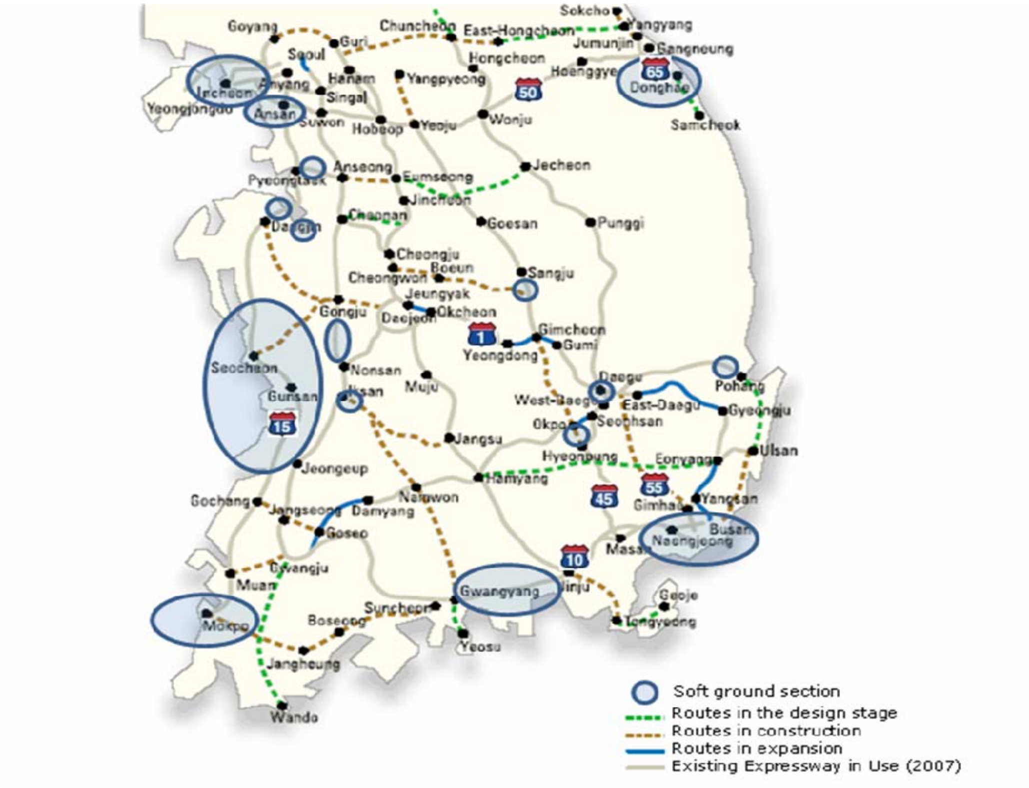

Figure 2. Soft ground section in Expressway of Korea

Table 1. Summary of soft ground section in expressway under usage

No. of Expressway	Section of soft ground		Length (km)	Main section	Remarks
	From	To			
15	0	14	3.3	Mokpo-Ilro	
	95	200	46.3	Julpo-Gunsan-Seocheon-Daecheon	
	284	334	4.2	Western Pyungtack-Seoksoo	
10	23	37	11.4	Okgok-Hadong	
	153	168	14.2	Nangjeong-Gupo in Busan	
104	6	14	7.4	Nangjeong-Sasang in Busan	Bridge is excluded
55	3	8	4.8	Daejeo-Daedong	
551	1	8	4.8	Daedong--Yangsan	
110	6	14	4.2	Incheon-Seochang	
45	9	21	6.1	Chilseo-Namji-(Youngsan)	
50	0	6	4.3	Seochong-Wallgot	
40	7	12	4.0	Pyungtack-Anseong	
Total			115.0		

Representative geotechnical parameters of the sections are briefly summarized in Table 2. More details of Busan, Incheon, Gwangyang, and Gunsan can be referred to the in Jung's thesis. [2]

Table 2. Representative geotechnical parameters of soft ground [3]

Site	Natural Water content w_n(%)	Water content w(%)	Plasticity Index PI(%)	Void ratio e	Unified Soil Classification
Busan Harbor	58 ~ 84	58 ~ 64	10 ~ 58	0.76 ~ 2.85	CH,OH
Masan Harbor	42 ~ 78	31 ~ 52	11 ~ 25	1.36 ~ 1.82	CL
Masan Gwigok-ri	101 ~ 148	107 ~ 130	58 ~ 82	2.81 ~ 3.48	CH,OH
Yeosoo	84 ~ 111	74 ~ 97	31 ~ 65	2.47 ~ 2.99	CH,OH
Sokcho Harbor	83 ~ 155	62 ~ 145	29 ~ 95	2.88 ~ 3.89	CH,OH
Nakdong river estuary	27 ~ 55	32 ~ 53	19 ~ 27	0.75 ~ 1.45	CL
Banweol	24.1 ~ 57.1	27.2 ~ 45.2	11.0 ~ 25.7	1.28 ~ 1.84	CL
Gwangyang	18.0 ~ 92.2	22.3 ~ 87.8	8.6 ~ 63.6	0.58 ~ 3.02	CH
Youngsang river estuary	47.1 ~ 68.7	32.4 ~ 55.6	16.6 ~ 2.23	1.45 ~ 2.23	CH,OH
Myeongjoo	64 ~ 226	144 ~ 150	3.8 ~ 5.04	3.8 ~ 5.04	OH,CH

3. ESTIMATION OF LONG-TERM SETTLEMENT

It is very difficult to directly measure the long-term settlements of an expressway during usage if not planned at the time of design. Korea's expressway only has a 40-year history. Industrial needs have priority over everything else and an expressway was required to be constructed and to be opened as rapidly as possible. As a result, there was not enough preparation for the management of long-term settlements and any monitoring data to make a reasonable inference of them. As a result, indirect but reasonable methods were developed to estimate the amount of long-term settlement of expressway after traffic is opened.

Firstly, relevant data was collected such as design drawings, design criteria, and specifications at the construction time. If necessary, personal interviews were conducted with engineers that had participated in both projects and who were managing maintenance. Next, levels of the present surface were taken for all the routes on soft ground, the total extending 115km. The coring of the pavement was then conducted to reveal the depth of the patch to be repaired and to compensate the rugged surface. As coring work is somewhat dangerous on the expressway when crowded with high-speed cars, a Ground Penetrating Radar (GPR) investigation was applied as a supplementary method. [4]

Leveling of Present Surface

Elevations of the present pavement surface were compared with those of the plan. In this case, the two sets of data between bridges were directly compared assuming that the abutments which have piled foundations installed into rock have not settled.

Because a numerical analysis revealed that Settlements caused by road embankments are almost constant on the whole top width of the road, leveling was taken on the shoulder of the expressway to prevent the interruption of traffic flow. [5] The measuring points were taken at a distance of 20 cm from the outer drive lane of both sides. The measuring interval along the route was 2-5m at the severely deformed approach area of a structure and mainly 20m elsewhere. Both longitudinal slope and unsymmetrical cross slope were applied according to the drawings and standards of the year of construction.

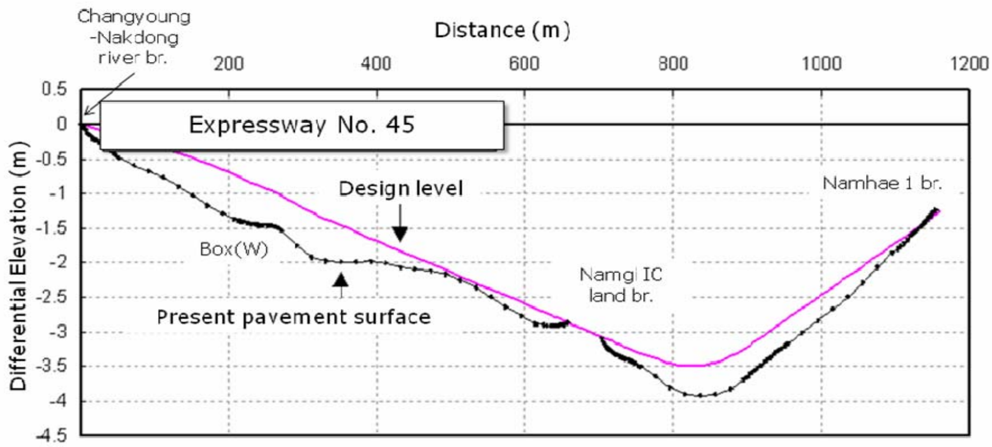

Figure 3. An example of leveling results

Figure 3 is an example of this result conducted on a section of the No. 45 Expressway around the Nakdong-river. Long-term settlement occurring in the middle of the embankment can be estimated using this figure but that near structures compensated by overlay is difficult to assume without the information of overlay-thickness.

Coring of Pavement

The rugged surface near the structure is repaired when the slope due to settlement exceeds the criteria of 1/200, in order to ensure both the safety and drivability of running vehicles. The main method used to even the slope is the overlay of pavement. The bridge approach section where the difference of long-term settlement between the structure and the embankment is relatively large has been overlaid many times. Therefore, the thickness of this overlay needs to be determined, and the most direct method, that of the coring of pavement, was used.

Coring was conducted at 180 locations where large long-term settlement was assumed at the preliminary investigation, mainly within 50m from the abutment of the bridge. The coring points were on the same longitudinal line as the leveling points. It was concluded that neither subtracting the designed thickness of the pavement from the overall coring length, nor multiplying the constant thickness by only the number of overlays, was adequate to match the actual long-term settlement. Changes of mixed aggregates and painting marks of the lane can be clues to identify the overlay (figure 4).

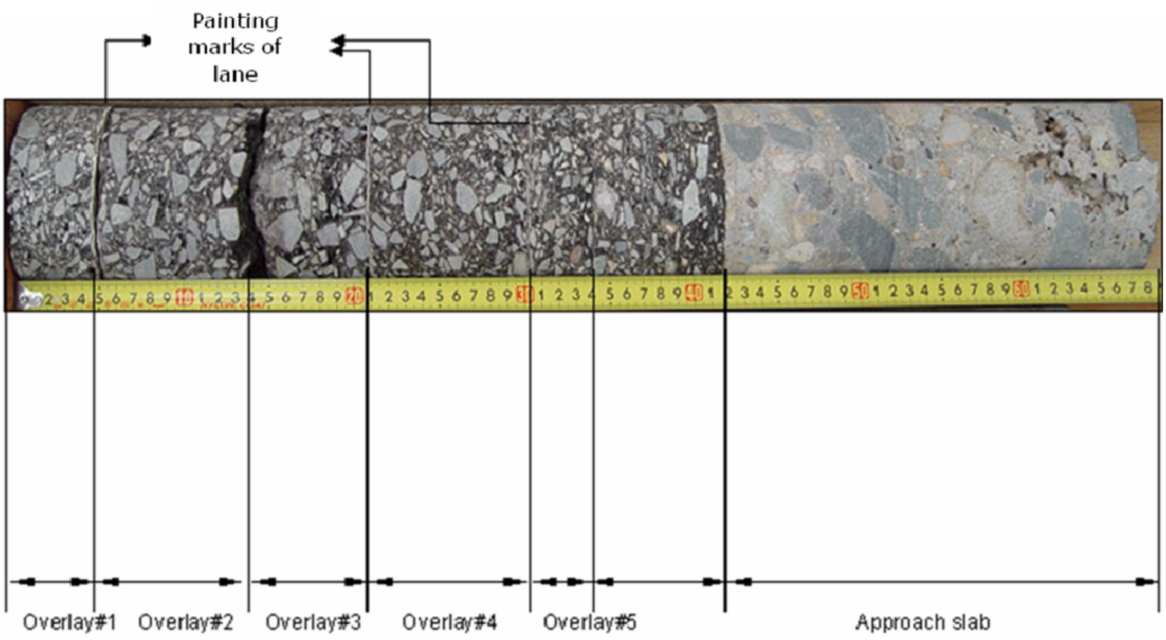

Figure 4. Example of core sample and identifying multi-overlays

Table 3 shows the results of overlaid thickness measured at the representative locations near the abutment of bridges where the long-term settlements are relatively large. There are considerable variances according to the Expressway and locations. The overlaid thickness reaches 30 - 60cm at the No. 10 Expressway, a considerable length of time after the traffic was opened.

Investigation of GPR

Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. GPR uses transmitting and receiving antennas, or either one of these containing both functions. The transmitting antenna radiates short pulses of the high-frequency (usually polarized) radio waves into the ground. When the wave hits a buried object or a boundary with different dielectric constants the receiving antenna records variations in the reflected return signal. A mobile GPR was performed using a vehicle system with a 1 GHz GSSI horn antenna for the GPR. The GPR vehicle system is sufficient for this purpose because it does not interrupt the traffic flow. The Namhae and Seohae expressways were investigated using the GPR vehicle system. Results of the GPR were compared with the cored samples of pavement and used as a supplementary method.

Table 3. Results of overlaid thickness at the representative locations

No. of Expressway	Direction	Locations	Overlaid thickness(cm)
20	Gangreung	10m apart from A2 of YG-IC-br.	18
		10m apart from A2 of YG1-br.	38
		10m apart from A1 of SR-br.	34
110	Incneon	10m apart from A1 of SSu-IC-br.	18
45	Hyunpoong	10m apart from A1 of CN-river-br.	28
15	Seoul	10m apart from A1 of GC-br.	6
		10m apart from A1 of HS1-br.	25
		10m apart from A2 of WK-br.	12
		10m apart from A2 of WK2-br.	9
55	Daedong	10m apart from A2 of KN-river-br.	19
		10m apart from A1 of DN-river-br.	38
551	Yangsan	10m apart from A1 of WC1-br.	20
		10m apart from A1 of YN-river-br.	22
		10m apart from A1 of YS-br.	31
		10m apart from A1 of SSa-br.	32
10	Suncheon	10m apart from A2 of SiE-br.	31
		10m apart from A2 of EB-br.	19
		10m apart from A1 of SJ-land-br.	17
		10m apart from A1 of KH-land-br.	32
		10m apart from A2 of HB-br.	25
		10m apart from A2 of BG-br.	15
		10m apart from A1 of HD-land-br.	43
	Busan	10m apart from A2 of CD-br.	34
	Suncheon	33.7k (embankment)	31
		10m/150m apart from A2 of JJc-br.	61/33
	Busan	5m/70m apart from A2 of KC-br.	39/43
		10m/20m apart from A2 of SuE-br.	51/58
		10m apart from A2 of JJ-br.	56
		15m apart from A2 of YS-br.	60
105	Jangyou	10m apart from A2 of PG-br.	34
		15m apart from A1 of SA-br.	50
		20m apart from A2 of JM-river-br.	47
		10m apart from A2 of SN-river-br.	23

Figure 5 shows the results of GPR investigated in the Namhae expressway as it passes through the Nakdong delta and while under heavy traffic after construction in 1996.

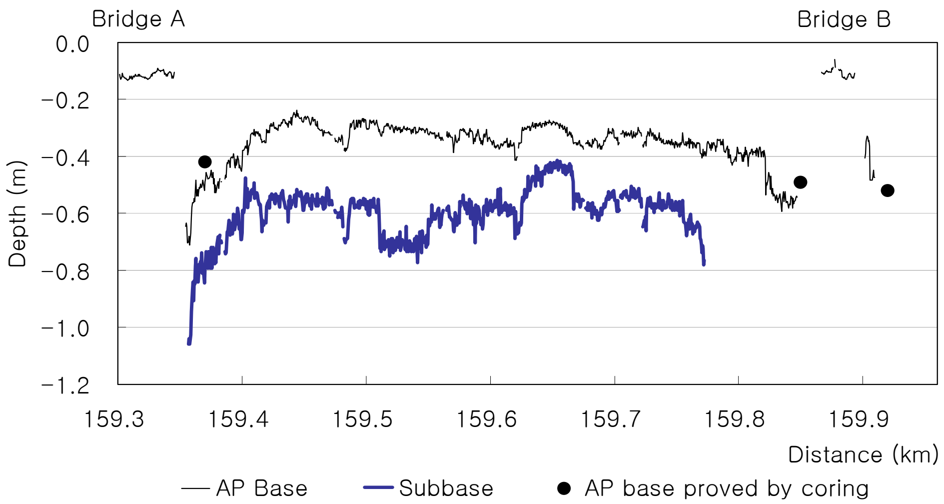

Figure 5. An example of the GPR result [4]

4. EVALUATION OF LONG-TERM SETTLEMENT

Long-term settlements are calculated by adding the difference of the elevation between the present surface of the pavement and design and the overlaid thickness. Table 4 shows the estimated long-term settlements for the distinctive sections of the No. 10, 15, 50 and 105 Expressways. The fact that the difference of elevation is relatively small but the thickness of the overlay is large in the approach section of the bridge proves that the management of the expressway has been concentrated in this section to level through the overlay. However, the settlement that occurred in the embankment section between bridges is comparatively uniform and does not need to be compensated.

It is evaluated that the long-term settlement is largest in the No. 10 Expressway, which has been in service for more than 20 years. Some sections of the No. 50 and 105 Expressways have settled more than 30cm. These sections are constructed on deep soft ground which has excellent compressibility.

Effect of thickness of soft ground

Estimated long-term settlements are shown according to the thickness of soft soils, D, in Figure 6. As the soft soils become thicker, the long-term settlements increase. However, the time effect is also included in this graph. It is known that the long-settlement of soft soil decreases as a function of elapsed log time. This can be expressed in Equation (1).

$$S = \alpha + \beta \log_{10} t \qquad (1)$$

Here, S is long-term settlement, t is elapsed time, and α and β are coefficients. β is especially related to the long-term settlement and called the coefficient of long-term settlement.

Table 4. Estimated long-term settlements for the distinctive sections

No. of Expressway	Section	Differences of El.(cm)			Thickness of Overlay	Average Long-term Settlement
		AVE	MAX	Approach		
50	SR-br. ~ WG1-br	20	25		20	20
	10m from A2 of SR-br			10	28	38
	10m from A1 of WG1-br			12	25	37
15	WC-br ~ KG-br	5	10			5
	GC-br ~ SJ3-br	25	30			25
	10m from A2 of GC-br			14	6	20
	10m from A1 of SJ3-br			8	7	15
	WG-br ~ KS-br	7	16			7
	10m from A2 of WG-br			5	12	17
	10m from A2 of WG2-br			10	9	19
	10m from A1 of KS-br			4	8	12
105	PG-br ~ SA-br	26	33		(5)	31
	10m from A2 of PG-br			6	34	40
	10m from A1 of SA-br			11	50	65
10	SJ-river-br ~ HD-tunnel	12	16		(5)	17
	JJ-br ~ NR-land-br	53	**100**		(5)	58
	10m from A2 of JJ-br			6	61	67
	PY-land-br ~ HB-br	30	48		(5)	35
	10m from A2 of PY-land-br			7	35	42
	10m from A2 of HD-land-br			10	32	42
	10m from A1 of HB-br			10	18	28

When the long-term settlements are normalized by elapsed time after the traffic has been open, they show the effect of the thickness of soft ground (Figure 7). The linear correlation that has an upper and lower boundary, with the exception of the dotted circle data, provides a possibility that long-term settlement is estimated if the thickness of soft ground is known. The thickness of the soft ground where the expressway was constructed varies from 10 m to 25 m and the elapsed time after service varies from 2 years to 11 years in this graph.

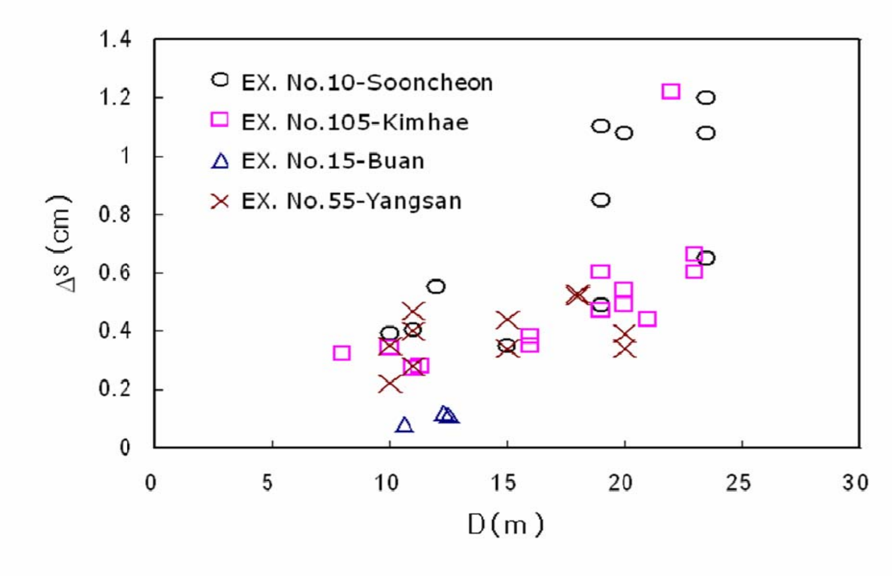

Figure 6. Long-term settlements(Δs) vs. thickness of soft soils (D)

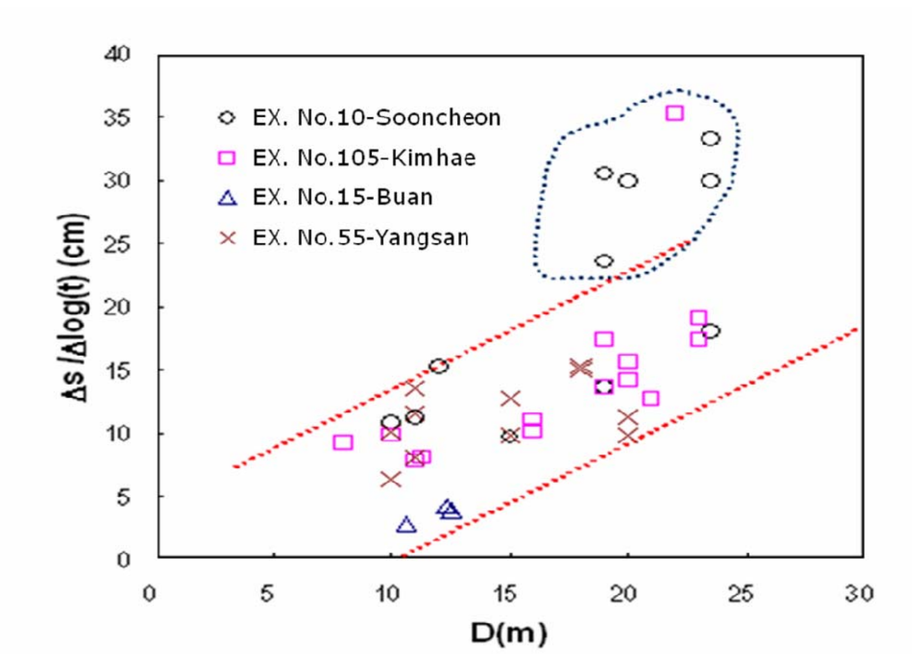

Figure 7. Normalized long-term settlements by elapsed time vs. thickness of soft soils (D)

There is some deviation in the data grouped within the dotted circle in Figure 7. This data shows that the locations have settled significantly more than other locations at the same elapsed time and thickness of soft ground. Several explanations are given for what causes these severe long-term settlements. Creep deformation by secondary consolidation, geometrical deformation of a 3-dimensionally shaped road, another long-term settlement caused by other deeper soft layers, and deformation by live loading can all be considered. It can also be assumed that primary consolidation was not completed at the locations or unimproved soft soil still remained even if the expressway was

open. Regardless of the main cause, it is established that these abnormal and severe settlements demand significantly higher costs..

5. CONCLUSIONS

Long-term settlements caused by secondary consolidation and other factors are inevitable when roads are constructed on soft ground. The settlement occurring during road usage threatens the safety of the road as it induces deformation and cracks on road structures and on the body itself. Moreover, it creates a rugged surface that deteriorates riding comfort and drivability. For this reason, while evaluating the settlement of the road after traffic has been open on soft ground is very important for the management of the road, it is very difficult to measure the long-term settlements directly.

For the expressway constructed on soft ground, long-term settlements after traffic was open were calculated as follows: first, the elevation of the present surface of the pavement was subtracted from that of the design and the overlaid thickness was then added. The overlaid thickness was measured by either coring the pavement or an investigation of GPR. The difference in elevations is relatively small but the thicknesses of the overlay were significant in the approach section of the bridge. The settlement, however, that occurred in the embankment section between bridges is comparatively uniform. It is evaluated that long-term settlement is the largest in the No. 10 Expressway, which has been in service for more than 20 years. At the approach section of the bridge in this line, the maximum settlement reached 100 cm. Some sections of the No. 50 and 105 Expressways have settled more than 30cm.

As the soft soils become thicker, the long-term settlements increase. The long-term settlements normalized by elapsed time after the traffic had been opened show a linear correlation having an upper and lower boundary. It is therefore possible that long-term settlement is estimated if the thickness of the soft ground is known.

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